Effects of optical thickness on soft X-ray spectral feature observed in Gd and Tb plasmas

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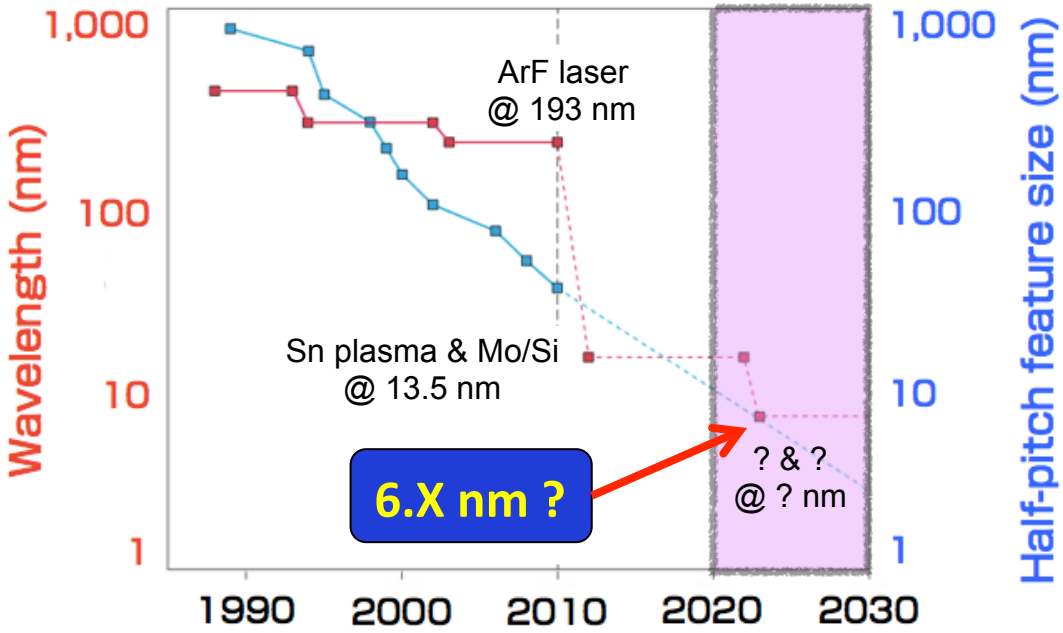
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Outline

- Introduction
 - BEUV lithography, fuels, opacity
- Experiments
 - CO_2/YAG LPP & LHD
 - Typical soft X-ray spectra from Gd/Tb plasmas
- Comparisons
 - Effects of opacity on spectral feature
 - Spectral purity & matching with MLMs
- Summary

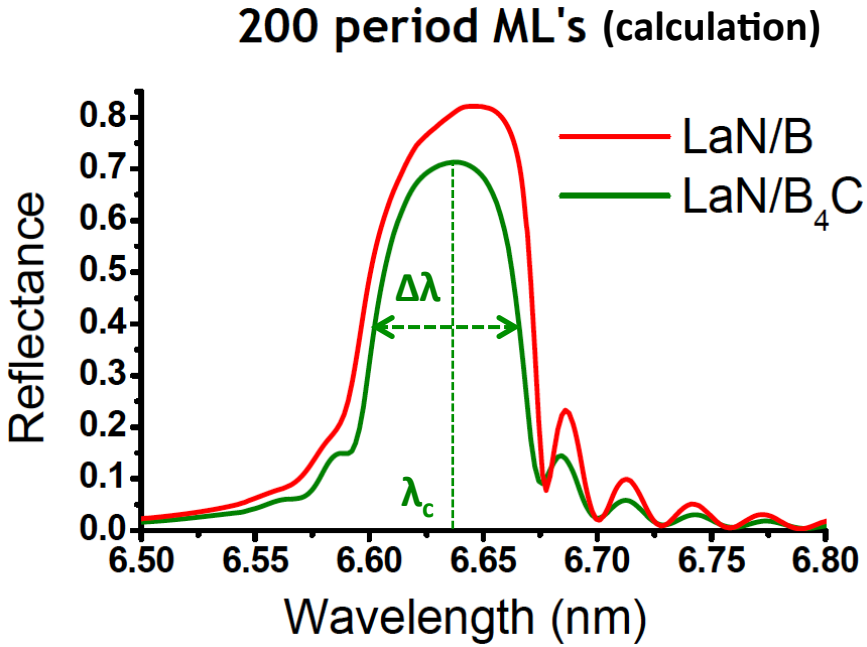
Beyond EUV lithography @ 6.X nm ?

Trend of LSI feature size



G. Tallents et al., Nature Photonics **4**, 809 (2010).

B-based MLMs @ 6.X nm ?



$\lambda_c \simeq 6.65$ nm

$\Delta\lambda \simeq 0.06$ nm (BW: $\simeq 0.6\%$)

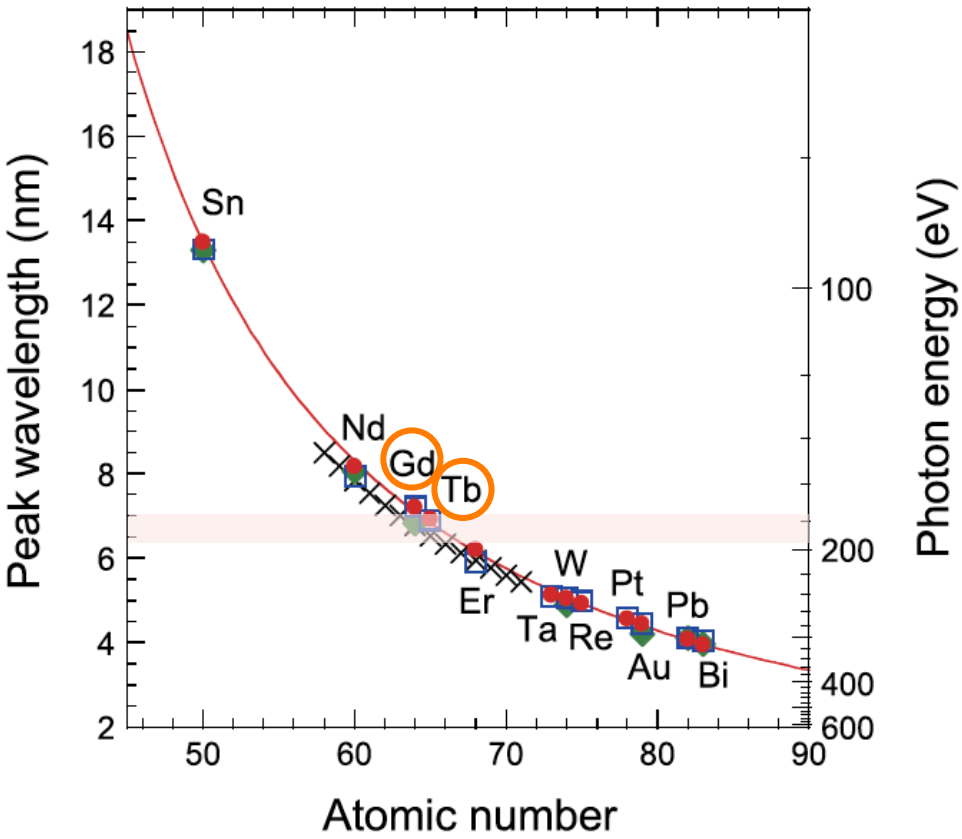
E. Louis et al., Proc. EUV & soft x-ray Source Workshop (2011).

Choice of fuels

Quasi-Moseley's law

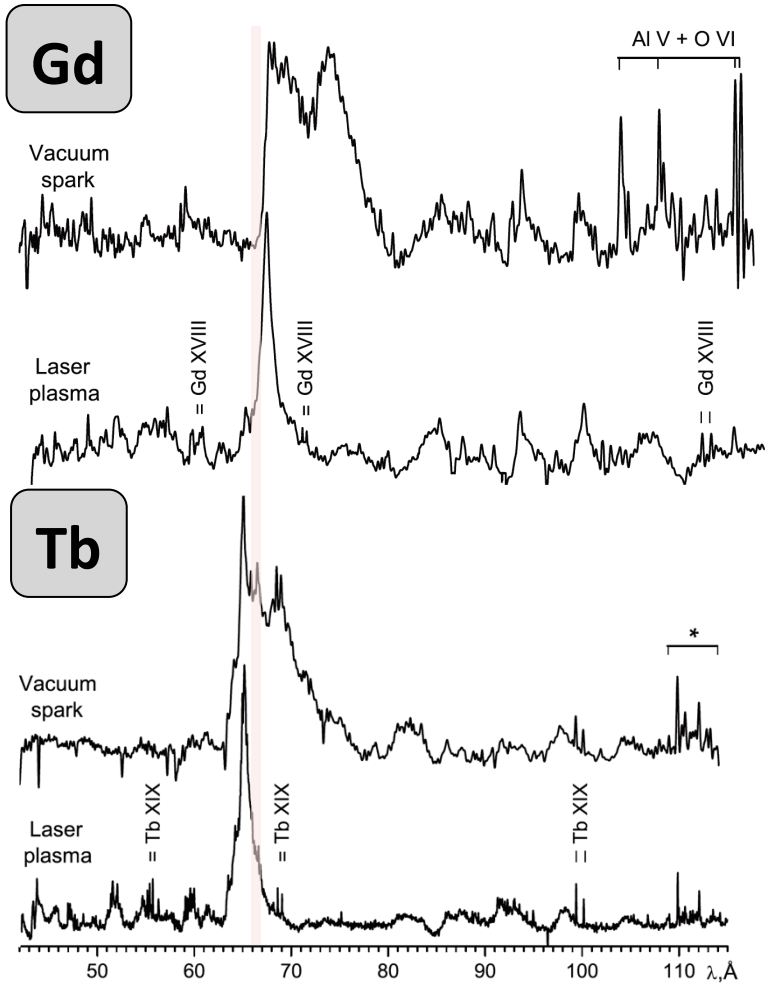
$$\lambda = aR_{\infty}^{-1}(Z-s)^{-b}$$

a =21.86, b=1.52, s=23.23



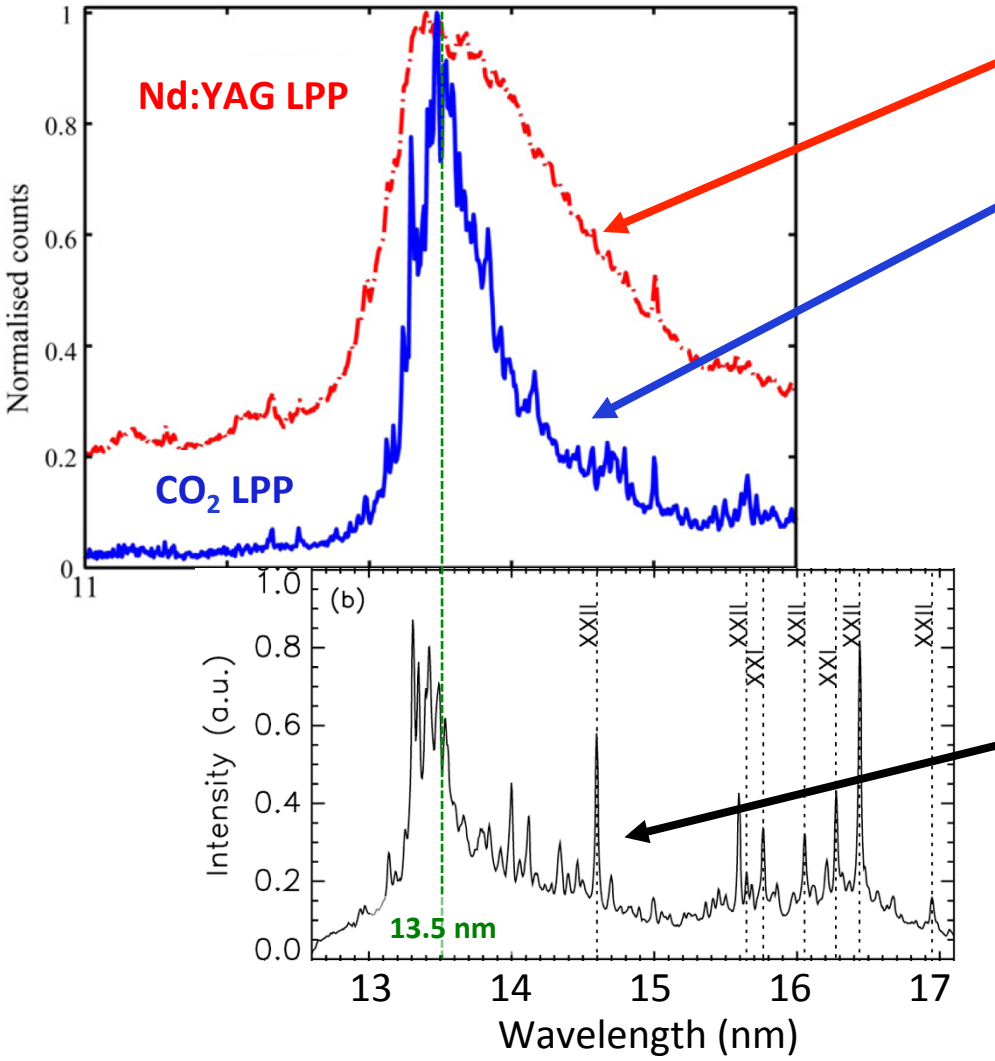
H. Ohashi et al., Appl. Phys. Lett. **104**, 234107 (2014).

Spectra @ 6.X nm



S. S. Churilov et al., Phys. Scr. **80**, 045303 (2009).

Opacity effects on Sn spectra



$n_e \simeq 10^{21}$ (cm^{-3}) λ_{laser} = 1.06 µm

$n_e \simeq 10^{19}$ (cm^{-3}) λ_{laser} = 10.6 µm

$n_c \propto \lambda_{laser}^{-2}$

G. O'Sullivan et al., Phys. Scr. **90**, 054002 (2015).

LHD
(magnetically confined fusion plasma)

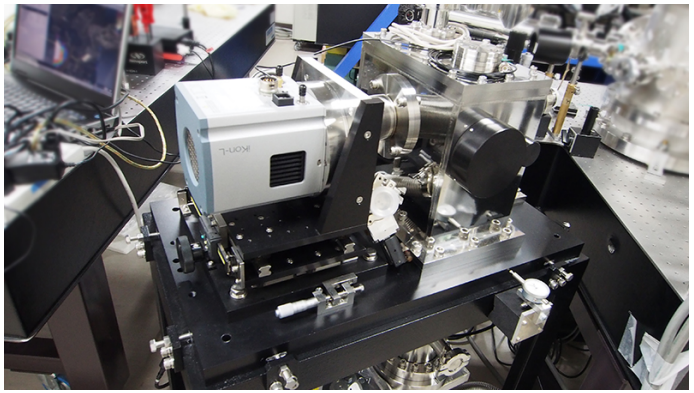
$n_e \simeq 10^{14}$ (cm^{-3})

C. Suzuki et al., J. Phys. B **43**, 074027 (2010).

The comparative study should also be helpful for BEUV (Gd/Tb).

CO_2/YAG LPP experiments

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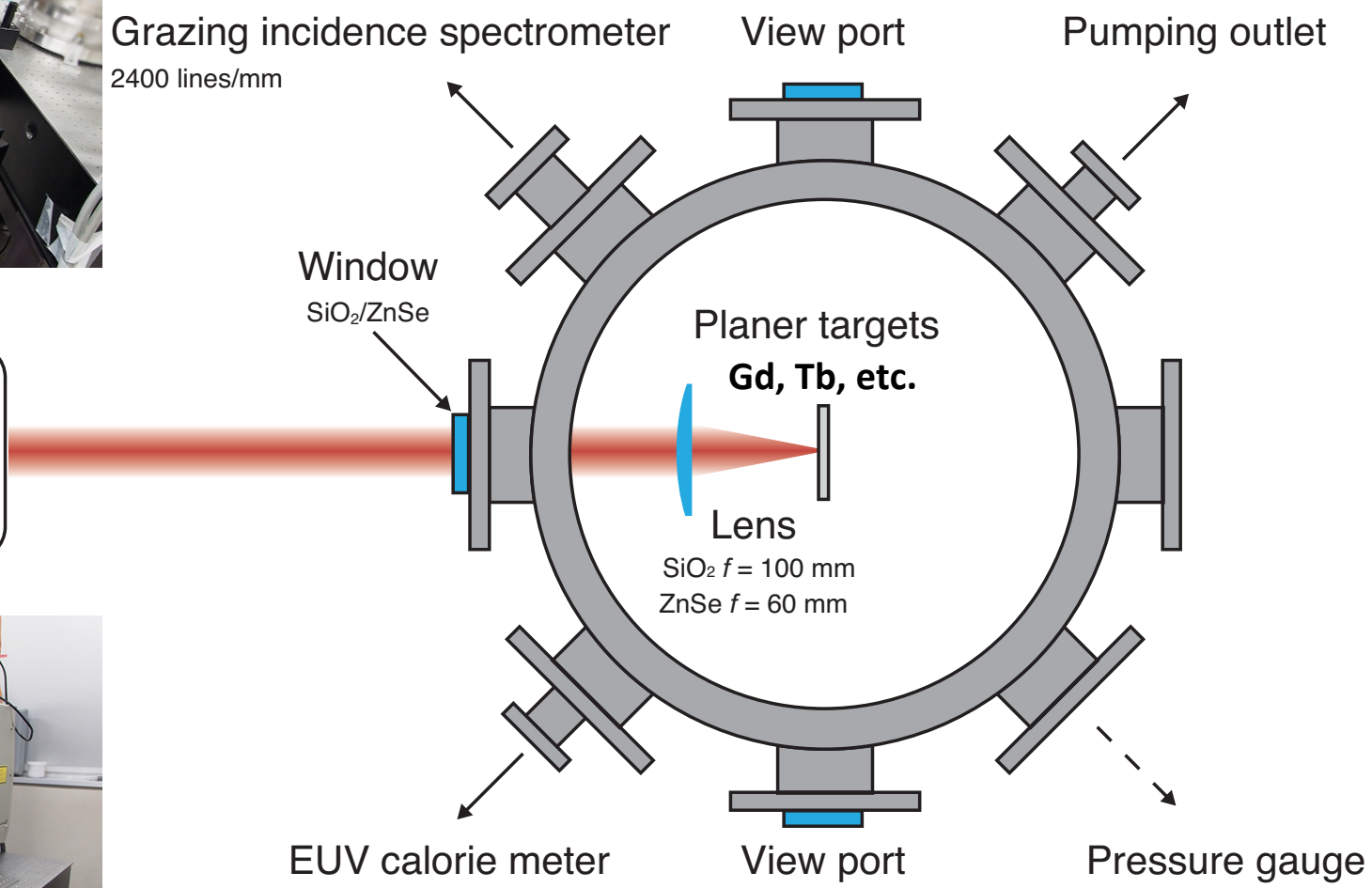
Lasers

Nd:YAG laser
1.06 μm, 10 ns, 1.3 J

CO_2 laser
10.6 μm, **5–15 ns**

Single shot mode

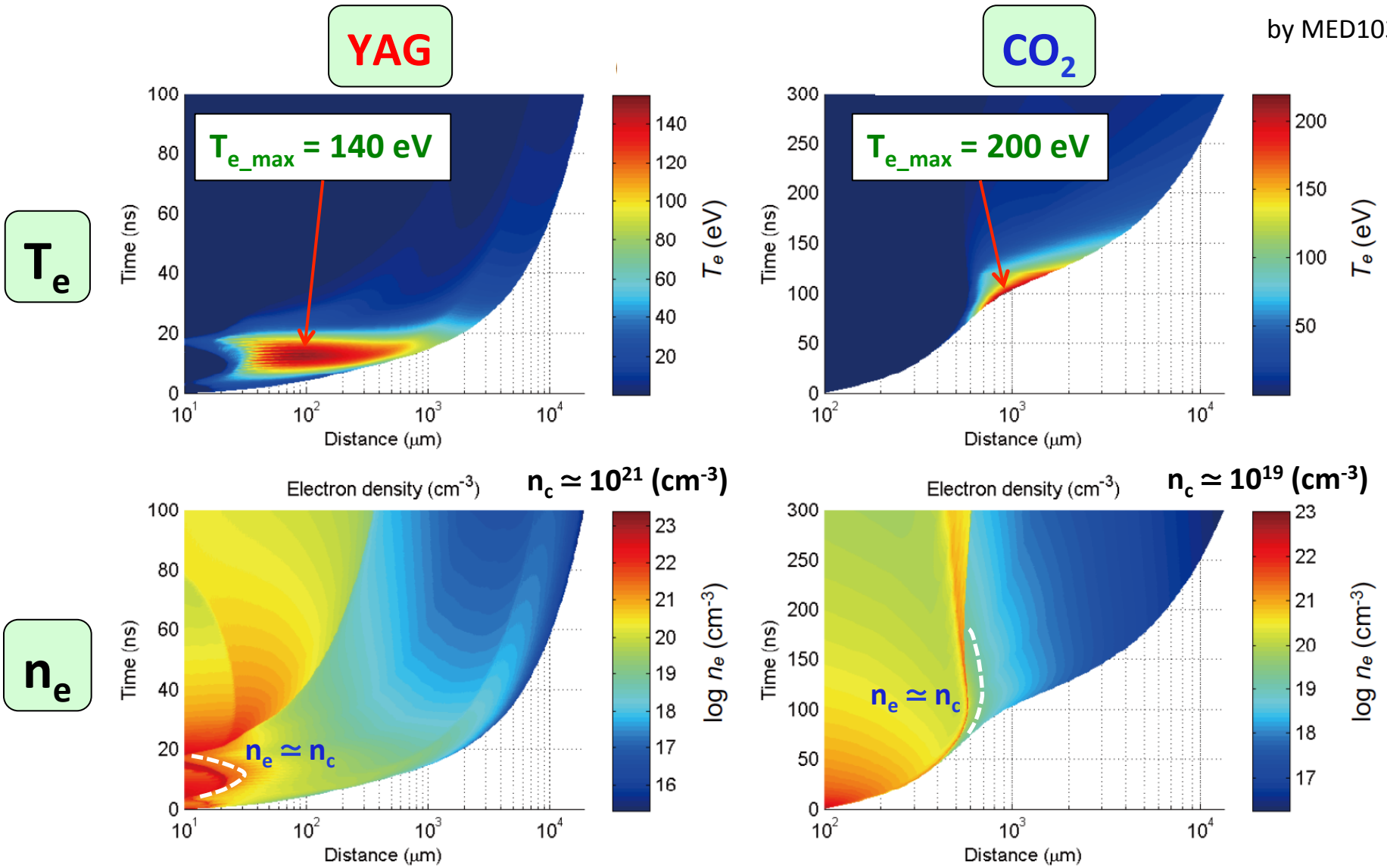




See poster S59 by Sasanuma et al.

Hydrodynamic simulation of Gd LPP

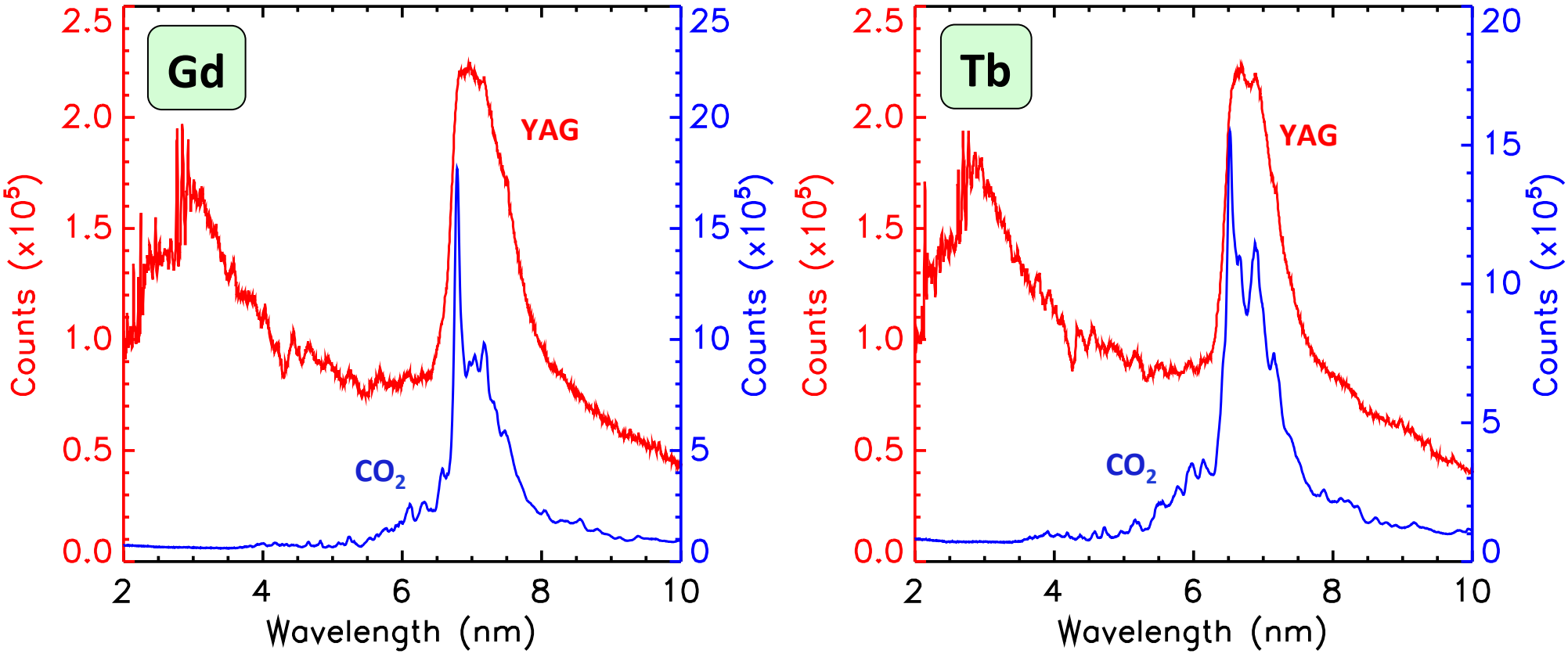
by MED103 code



T. Higashiguchi et al., Opt. Express **21**, 31837 (2013).

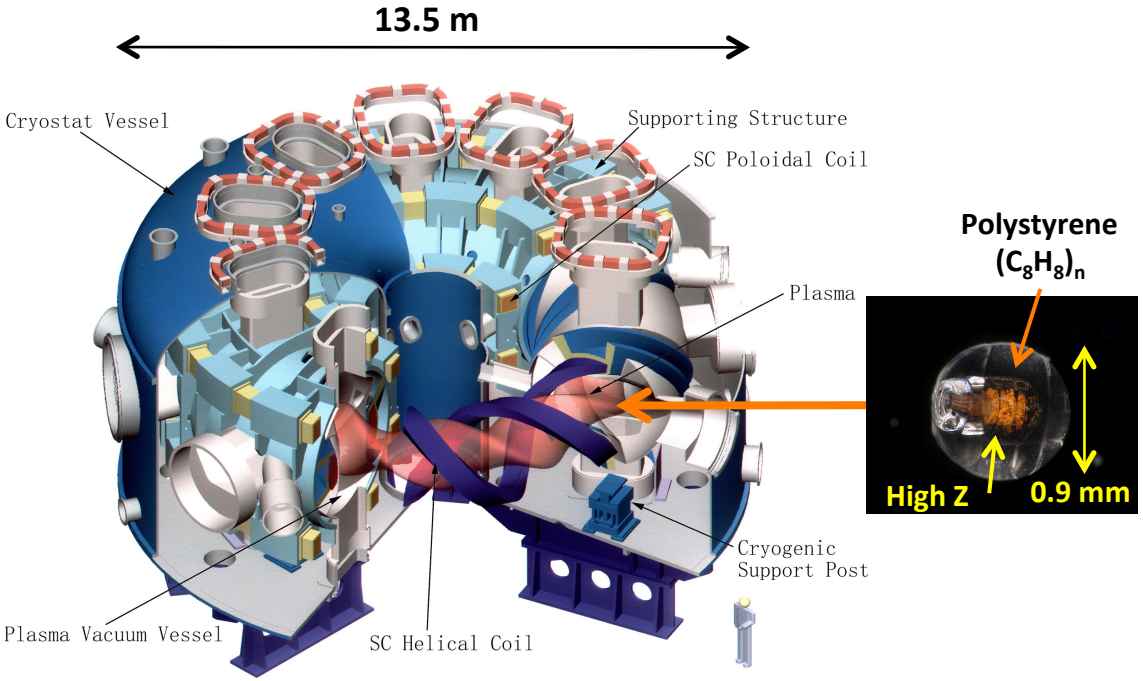
Typical soft X-ray spectra from CO_2/YAG LPPs

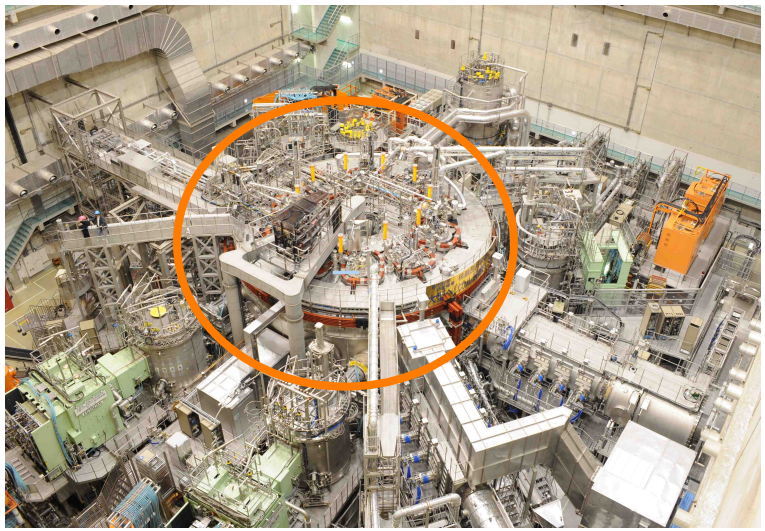
CO_2: 2.3×10^{10} W/cm^2 × 40 shots
YAG: 4.8×10^{13} W/cm^2 × 1 shot



Better spectral purity in optically thin CO_2 LPPs

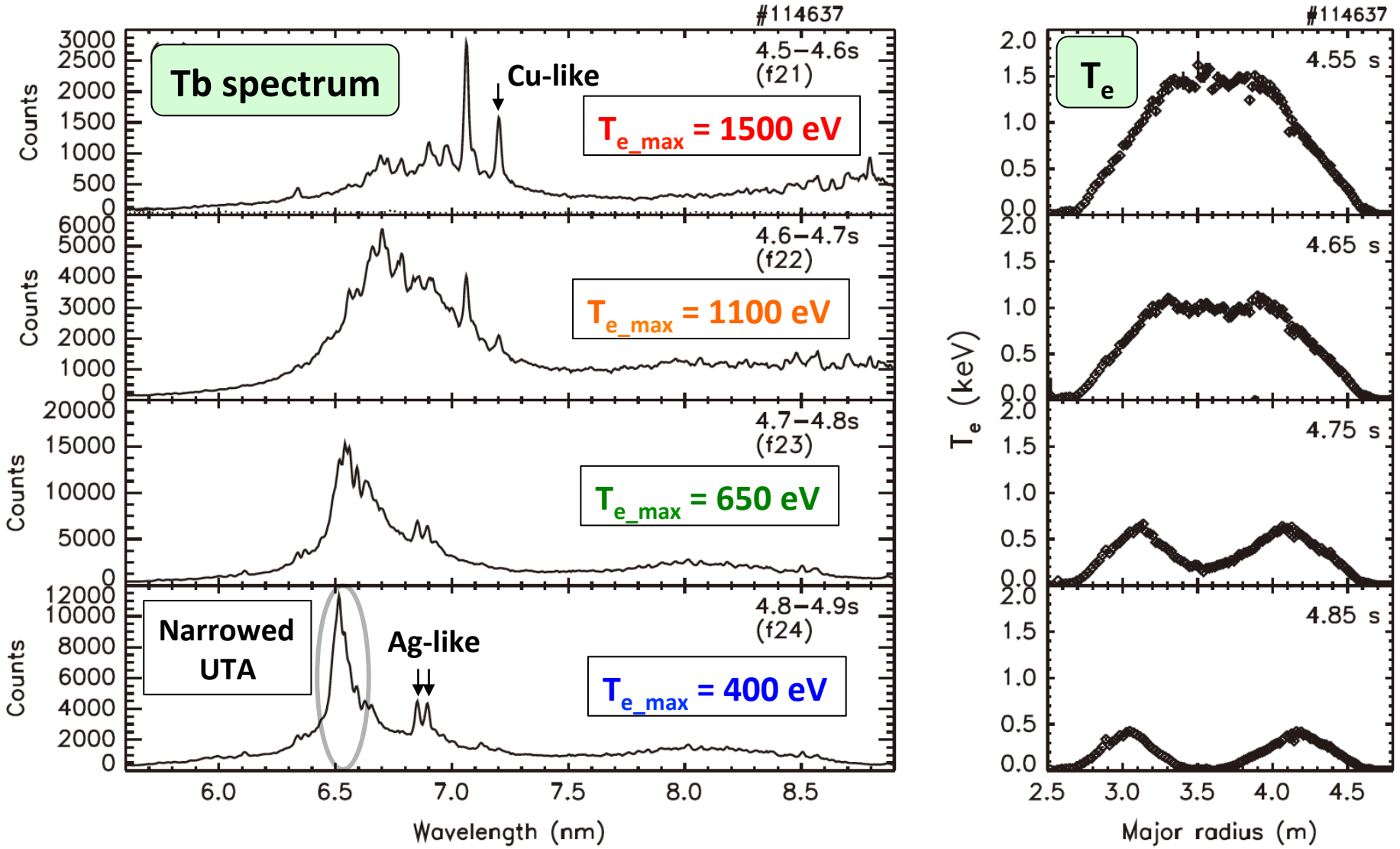
Large Helical Device (LHD): extremely low opacity





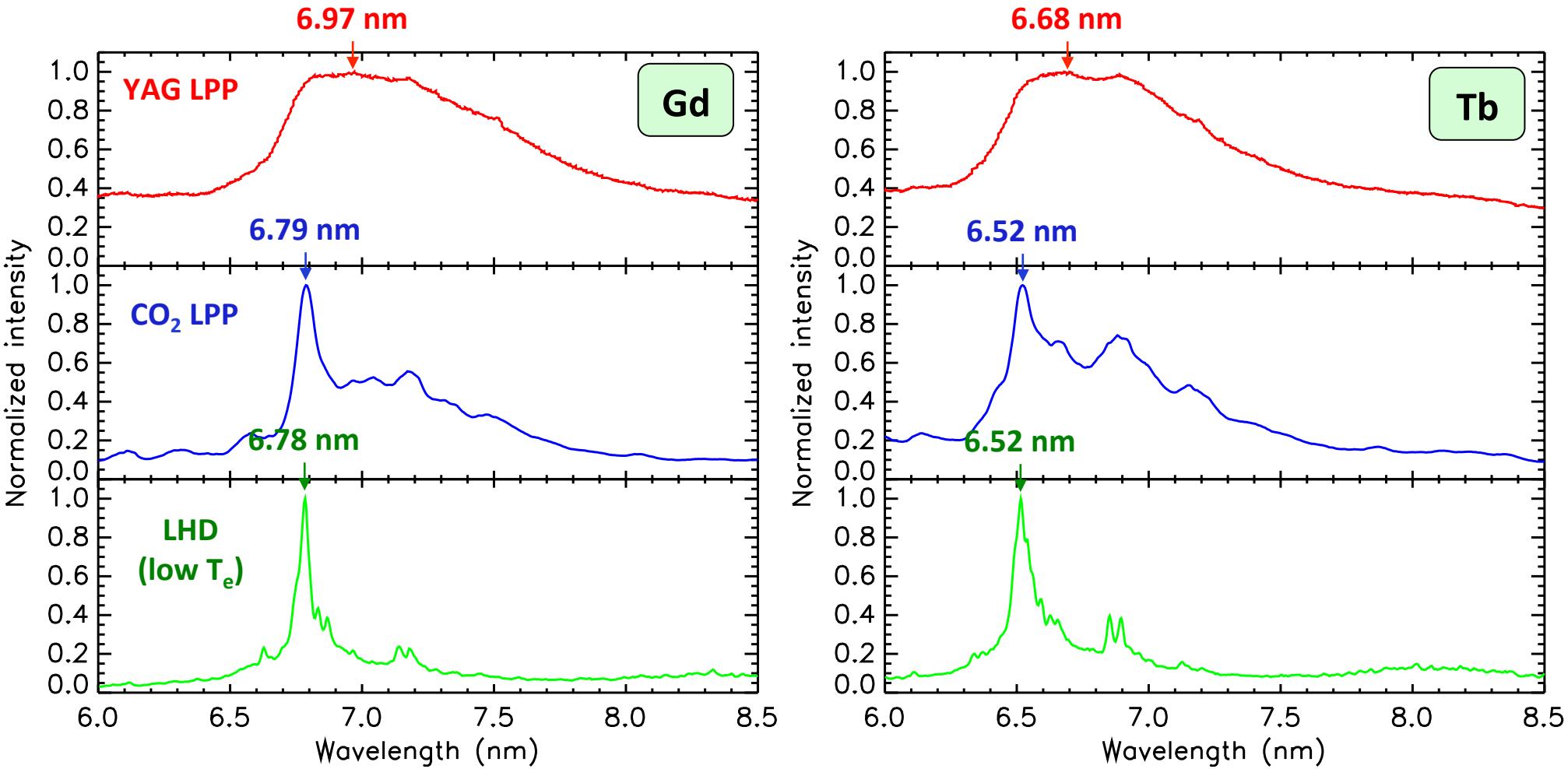
- Large-scale facility for magnetic confinement fusion @NIFS
- $T_e \simeq$ 100 eV – a few keV ; $n_e = 10^{12}$–10^{14} cm^{-3}
- Large plasma volume ($\simeq$ 30 m^3)
- Impurity pellet injection system (TESPEL)

T_e dependence of high Z spectra in LHD



C. Suzuki et al., J. Phys. B: At. Mol. Opt. Phys. **48**, 144012 (2015).

Comparison among three sources



Wavelengths of the resonance line of Pd-like ions: $4d^{10}\ {}^1S_0 - 4d^9 4f\ {}^1P_1$

J. Sugar and V. Kaufman, Phys. Scripta **26**, 419 (1982).

Gd^{18+}: 6.76 nm

Tb^{19+}: 6.51 nm

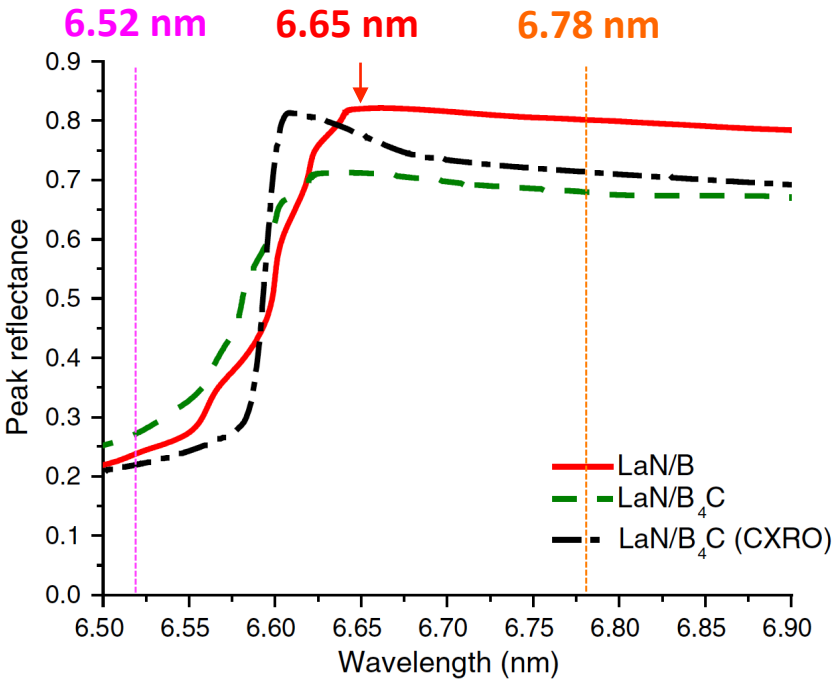
Spectral purity & MLM reflectance

Spectral purity ≡ $\int_{\lambda_c-0.03}^{\lambda_c+0.03} I(\lambda)d\lambda \Big/ \int_{6.0}^{8.5} I(\lambda)d\lambda$

(Δλ ≃ 0.06 nm)

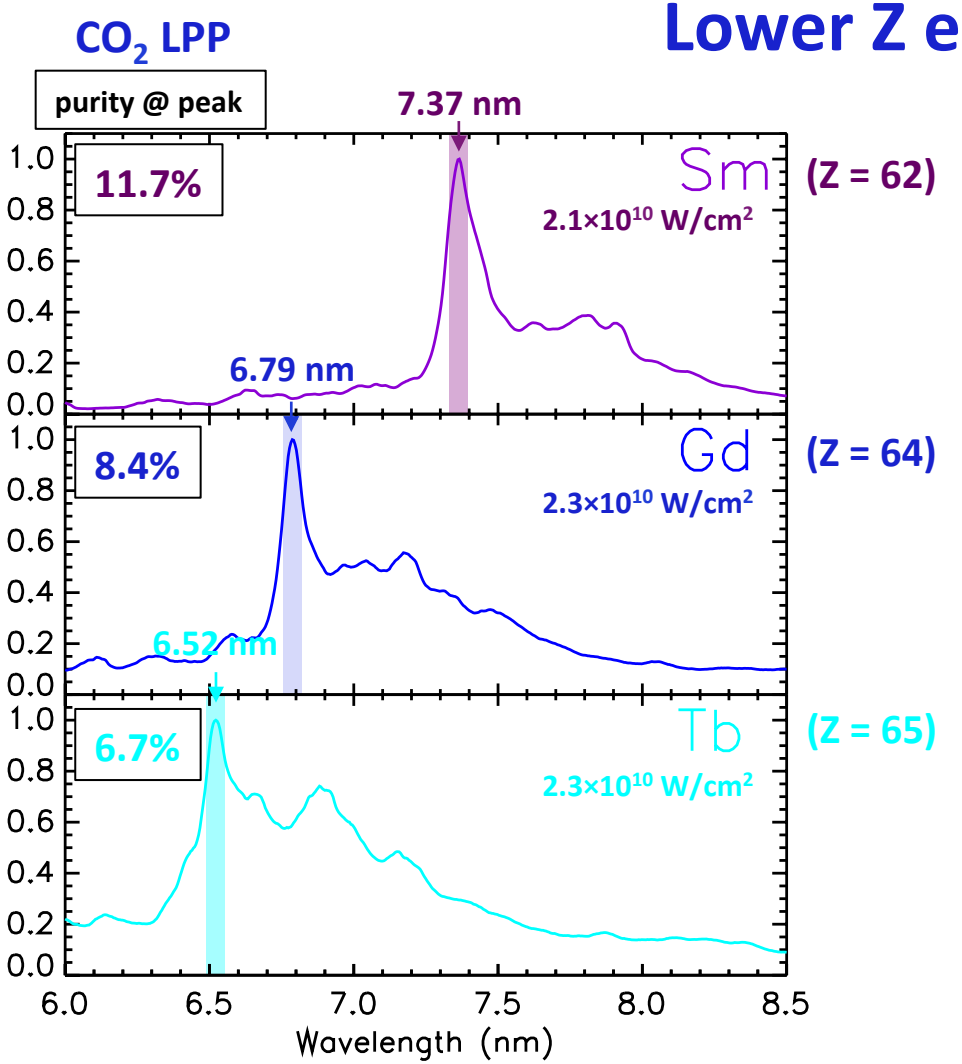
		λ @ peak	Spectral purity	
			@ peak	@ 6.65 nm
Gd	YAG	6.97 nm	4.1%	2.4%
	CO_2	6.79 nm	8.5%	2.1%
	LHD	6.78 nm	14.2%	3.7%
Tb	YAG	6.68 nm	4.2%	4.2%
	CO_2	6.52 nm	6.8%	5.1%
	LHD	6.52 nm	12.0%	5.2%

R_{peak} of a perfect MLM (Calculation)

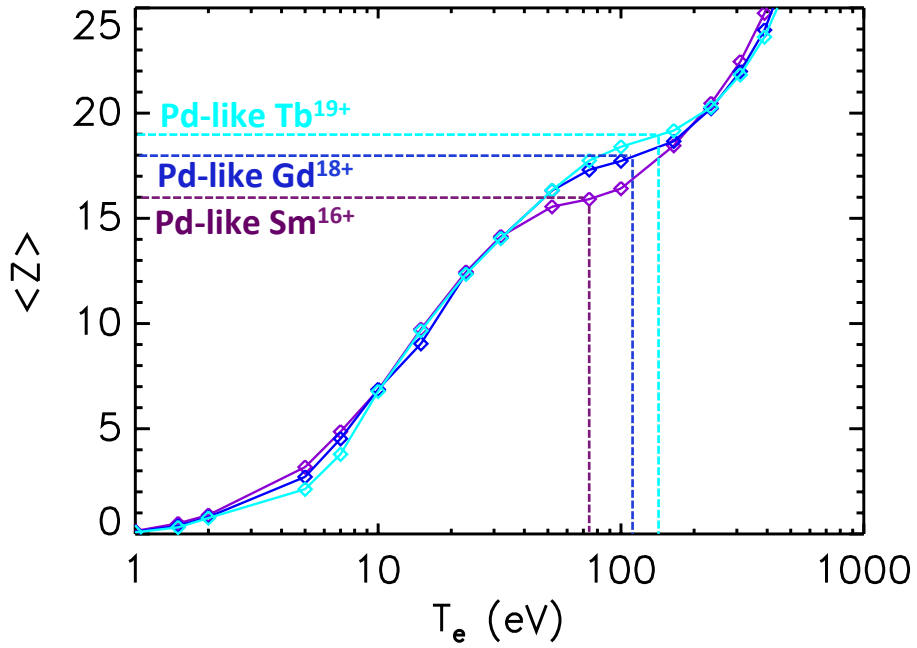


I. A. Makhotkin et al., J. Micro/Nanolith. MEMS MOEMS **11**, 040501 (2012).

Lower Z elements ?



Average charge vs. T_e
(rough estimation by FLYCHK code)



- **Use of lower Z elements (e.g. Eu, Sm)**
 - ◎ **Better spectral purity @ peak @ same laser energy, Pd-like ions @ lower T_e**
 - △ **Perhaps lower reflectance of B-based MLM**

Summary

- We have made comparisons among three types of soft X-ray spectra from Gd and Tb plasmas with different opacities: CO_2/YAG LPPs and LHD plasmas.
- In contrast to YAG LPP, the spectral feature of CO_2 LPP is closer to that of LHD plasmas: an ideally low opacity condition.
- Sharp peaks of Pd-like resonance line are outstanding in CO_2 LPP and LHD plasmas, which leads to better spectral purity.
- The spectral purity of CO_2 LPP at each peak is better for lower Z lanthanide elements at the same laser energy.